Designing District Heating Systems for an Improved Economic Efficiency: A Case Study of a Renewable Rural District Heating Network

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Abstract

In the design phase of district heating networks many parameters that determine the economic efficiency of the network must be chosen. This contribution investigates the economic effects of the choice of the piping system (single or twin pipes), the maximum specific pressure drop, and the return temperature for a rural district heating network. The economic analysis takes costs for network construction and maintenance, heat losses and pump energy into account. The results show that the design variant using twin pipes, pipe dimensioning to 250 Pa/m and network temperatures of 80 °C flow and 45 °C return is most cost efficient, with heat distribution costs of 3.7 €ct/kWh. This is a cost reduction of 20 % in comparison to the reference variant with single pipes, pipe dimensioning to 120 Pa/m and network temperatures of 80 °C flow and 60 °C return.

Keywords: district heating network, design, dimensioning, heat distribution costs

1. Introduction

District heating networks (DHN) are a key technology to integrate renewable heat sources such as solar, biomass, waste heat or combined heat and power generation into future sustainable heat supply systems. While urban areas have high heat demand densities which are favorable for the economic efficiency of DHN, achieving reasonable heat distribution costs in rural areas is a challenge.

During the planning phase of a DHN, many parameters that strongly influence its future economic performance are determined. Of high importance are the choice of the piping type and the network temperatures. Another essential factor are the individual diameters of the pipes, that are usually determined by choosing a maximum specific pressure drop that is allowed at design conditions. In the literature, many different recommendations for the choice of the maximum specific pressure drop can be found, ranging from 100 Pa/m up to above 300 Pa/m (Best et al., 2018). In this contribution, an optimized design for a DHN in a rural area is developed considering these parameters.

2. Case Study

The DHN investigated here is currently in the planning phase. The heat will be generated from wood chips (wood scrap material) in the base load and from biogas, using highly flexible combined heat and power units that will be operated such that they help balance fluctuating renewables. Thus, the heat generation is fully renewable and has additional positive effects for the integration of renewables into the electricity sector.

The DHN shall supply a small village (90 household connections) and a large public property with heat (see fig. 1). The total trench length is about 6 km, while the linear heat density of 730 kWh/(m·a) is rather low. The local conditions entail long transport pipes from the heat supply unit to the village and the public property that make up about half of the total trench length.

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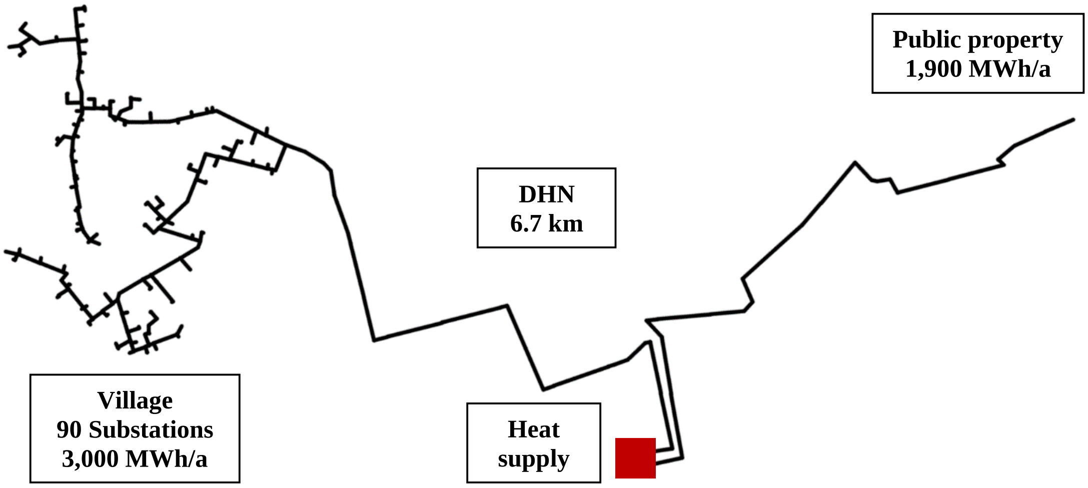


Fig. 1: The rural DHN. Two transport pipes, each about 1.4 km, connect the heat supply unit with the village (90 substations) and the large public property.

The heat customers in the village are single-family and small multi-family buildings, among which only a few have been constructed recently, so that the building stock exhibits a high specific heat demand of 150 kWh/(m^2·a) on average. In the village, the network shall be operated year-round, while the summer heat demand of the public property will be met locally, so that this transport pipe can be shut down for three months.

3. Methods

3.1. Calculation of the maximum heat power

The design process of the DHN starts with determining the maximum heat load that may occur. From another project, detailed calculations of the heat load of the residential buildings in the village, that take heat losses through the building envelope and solar gains into account, are available. Based on these load profiles, the maximum heat load at an ambient temperature of -12 °C (standard ambient temperature for heat load calculations in this area according to Deutsches Institut für Normung e.V., 2008) is calculated.

The additional heat power to provide domestic hot water is included according to the German standard DIN 4708 (Deutsches Institut für Normung e.V., 1994). For this calculation, information about the number of inhabitants and living space is used and a domestic hot water preparation with a storage volume of 30 l/person is assumed.

For each of the 90 residential buildings, maximum heat powers ranging from 8 kW to 41 kW that sum up to 1.54 MW are determined. The public property has a maximum heat power of 2.14 MW, so that in total, a maximum heat power of 3.7 MW must be provided by the DHN.

3.2. Simultaneity

Not all heat customers need the maximum heat power at the same instant, so that the maximum instantaneous heat load for the DHN is less than the sum of all individual maximum heat loads. This effect is described by the simultaneity factor, that can be determined according to equation 1 and is restricted to values from 0 to 1.

$$f_{\mathrm{sim}} = \frac{\max\limits_{t}\left(\sum_{i=1}^{N} \dot{Q}_i(t)\right)}{\sum_{i=1}^{N} \max\limits_{t}\left(\dot{Q}_i(t)\right)} \qquad \text{(eq. 1)}$$

with:

f_{sim}	Simultaneity factor
N	Total number of heat customers
$\dot{Q}_i(t)$	Heat power of the customer i at time t

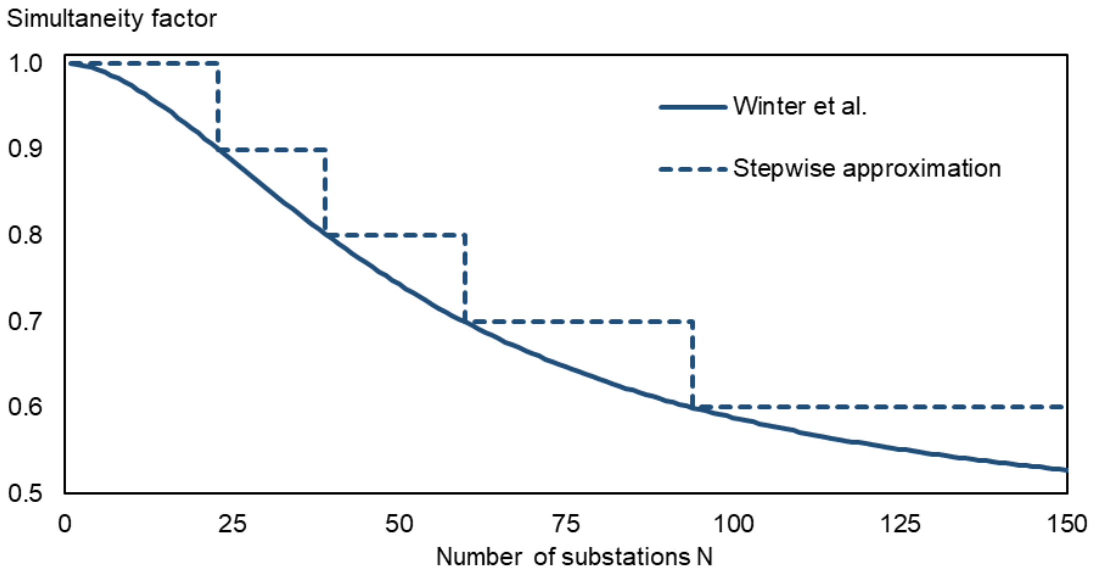


Fig. 2: Empirical simultaneity factor (Winter et al., 2001).

In the literature, various approaches to calculate the simultaneity factor with respect to the total number of customers N can be found. In this contribution, an empirical formula is used, that has been determined using a large data base from DHNs with a customer composition similar to this case study (Winter et al., 2001). This simultaneity factor is calculated as a stepwise approximation (steps of 0.1) in the design process of the network (see fig. 2). When determining the diameter of a pipe segment, the simultaneity factor according to the number of substations N downstream the pipe segment is used to adapt the maximum power that the respective pipe segment shall meet.

3.3. Design variants

In total, five different design variants are considered. All of them use pipes with insulation series 3 (the particular specification is according to Isoplus “konti” pipes, according to Koidl, 2016) in order to limit heat losses to a minimum despite the rather low linear heat density of the DHN. Furthermore, a design flow temperature of 80 °C is chosen for all design variants.

The reference design variant uses single pipes that are designed with a maximum specific pressure drop of 120 Pa/m and a return temperature of 60 °C, without taking simultaneity factors into account. The return temperature of 60 °C is a high return temperature, that must be expected for customers with unsatisfactory secondary installations (no hydraulic balancing, inefficient domestic hot water preparation and storage).

The following design variants change these parameters step-by-step, whereby from one to the other the parameter is chosen, for which the best relation of benefit to effort is anticipated. In this way, twin pipes, a high maximum specific pressure drop of 250 Pa/m, a return temperature of 45 °C and the consideration of simultaneity factors are investigated.

3.4. Pipe dimensioning

The dimensioning of the pipe network is carried out with a thermo-hydraulic model in the commercial software STANET® (Fischer-Uhrig, 2019). First, a detailed model of the DHN is built and parametrized, that represents the piping route including all house lead-in pipes.

For each variant, volume flow rates at maximum load conditions are determined for every pipe segment in consideration of the maximum heat loads of the substations, design temperatures of the network and, if applicable, the simultaneity factors. Then every pipe segment’s diameter is determined, such that its specific pressure drop is only just below the maximum specific pressure drop (120 Pa/m or 250 Pa/m). At this, the pressure loss calculation takes individual points of flow resistance into account using a generalized estimation based on the length and the diameter of the pipe segment. This dimensioning procedure is carried out iteratively, as changes in pipe diameters entail minor changes in flow temperatures at the substations. A stable result is reached after no more than three iterations.

3.5. Determination of heat losses and pump energy demand

For each variant, heat losses and pump energy demand for a whole year are determined using thermo-hydraulic simulations. The precalculated heat load profiles for each customer are available at a resolution of one hour. Additionally, load profiles for domestic hot water are generated for each substation individually using the DHWcalc tool (Jordan et al., 2017). The effects of secondary installations (time shifts, losses) are neglected at this stage. The total load profile for all loads is split into two parts, first for the heating season (mid of September until mid of June) and second for the summer period, when the network section to the public properties will be shut down, so that this period must be considered separately. In fig. 3 the load duration curves (sorted hourly load values) for both periods are depicted. To limit the effort for simulations and calculations to a reasonable extent, the load duration curves are classified into six (heating season) and three (summer) load classes, each with a constant power and a suitable duration, that represent the load duration curves, as shown in fig. 3. Instead of simulating the whole year in hourly resolution, these representative load states are simulated, and the results are extrapolated according to the respective duration of each load class.

These nine representative load states are simulated for each design variant using the thermo-hydraulic model in STANET® to determine heat losses of the DHN as well as volume flow rates and differential pressures of the network pumps. The heat loss calculation includes the interaction between flow and return pipe of twin pipes in a simplified way: The heat loss coefficients for the twin pipes are set according to heat flows at typical temperatures (75 °C flow / 50 °C return / 10 °C soil temperature), which results in low heat losses from return pipes, as they gain some heat from the flow pipes. In the simulations, as a simplification, a constant return temperature according to the design variant (60 °C or 45 °C) is assumed at the consumer substations. However, the variable flow temperature is 70 °C in summer and rises linearly to 80 °C, while ambient temperatures fall from 15 °C to -10 °C.

The electric power consumption of the pump motor is calculated from volume flow rate, differential pressure, and the total pump efficiency (including motor efficiency) according to equation 2.

$$P_{\mathrm{pump}} = \frac{\dot{V}\,\Delta p}{\eta_{\mathrm{pump,tot}}} \qquad \text{(eq. 2)}$$

where

P_{pump} electric power consumption of the pump motor
$\dot{V}$ volume flow rate
Δp differential pressure
$\eta_{\mathrm{pump,tot}}$ total pump efficiency (including motor efficiency)

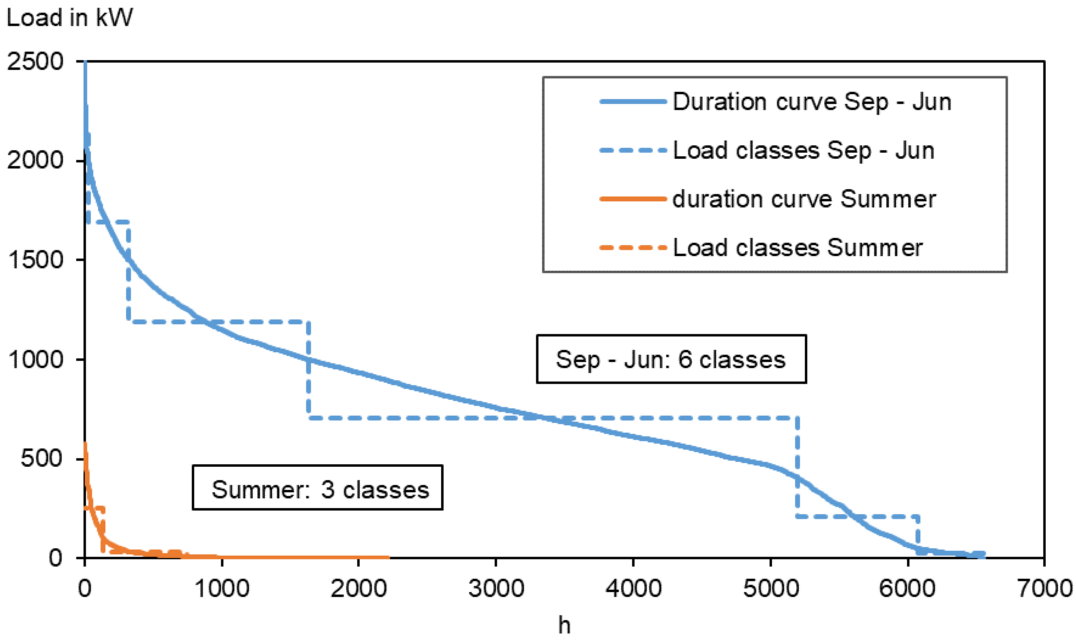


Fig. 3: Load duration curves for heating season (mid of September until mid of June) and the representative load classes.

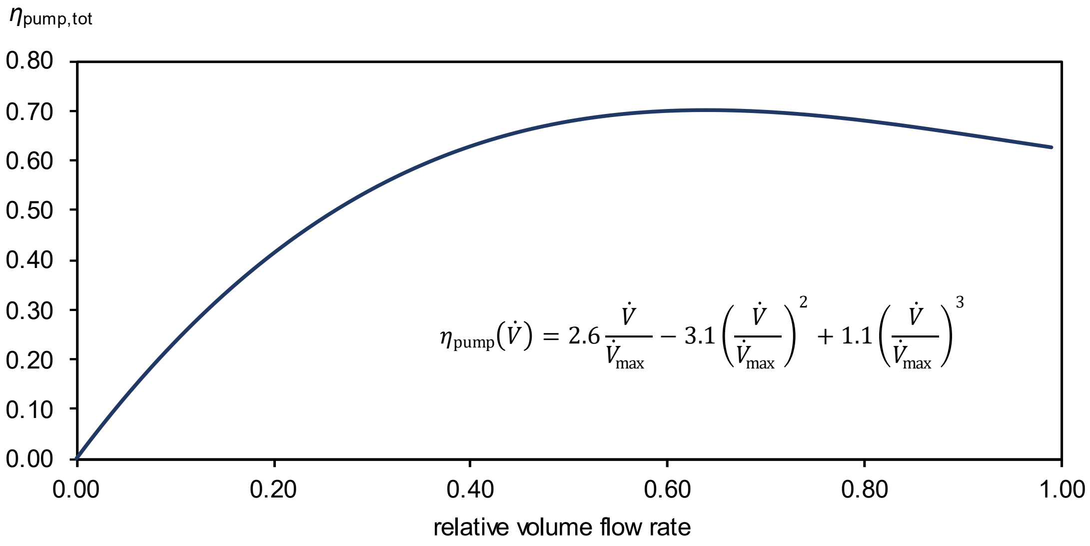


Fig. 4: Assumed total pump efficiency as a function of relative volume flow rate.

The total pump efficiency depends on the type of the pump and in general depends on the volume flow rate. In this contribution, the generic approximation for the total pump efficiency depicted in fig. 4 is used. It shows a very low total pump efficiency at low volume flow rates, reaches a maximum of 70 % at medium and high volume flow rates and finally drops slightly towards maximum pump capacity. The speed of the pump is controlled so that a minimum differential pressure of 0.6 bar at the consumer substations is maintained. In this case study, only a single pump is assumed. In cases where several pumps with different capacities are installed, high pump efficiencies even during low load perios are possible by using the smaller pump, which reduces the electricity consumption of the pumps.

Based on the values for pump and heat loss power for each representative load state, annual values are extrapolated according to the duration of each state.

3.6. Calculation of heat distribution costs

Based on the results of the previous steps, the heat distribution costs per delivered heat are calculated, whereby construction and maintenance of the DHN including substations, costs for heat losses and costs for pump energy are included.

The network construction costs for each pipe segment are calculated according to a cost approach that specifies costs for each pipe depending on the its diameter and the ground condition (green area or paved surface, see fig. 5) (Manderfeld et al., 2008).

The costs include the pipe itself, ground works, pipe installation and restoration of the ground surface. It is assumed, that the network costs for single and twin pipes do not differ significantly from each other (Manderfeld et al., 2008). The transport pipes will be laid in green areas, whereas the distribution pipes in the village will be laid in streets, so that costs for paved surfaces apply.

The heat distribution costs are determined via a dynamic economic analysis as an annuity, which is finally divided by the annual heat delivery, to ensure the comparability of the results. The important parameters of the economic analysis are summarized in table 1. The values are taken from the literature or are chosen by the DHN operator of the case study, as indicated in the table. Subsidies, price increase and inflation are excluded from the economic analysis.

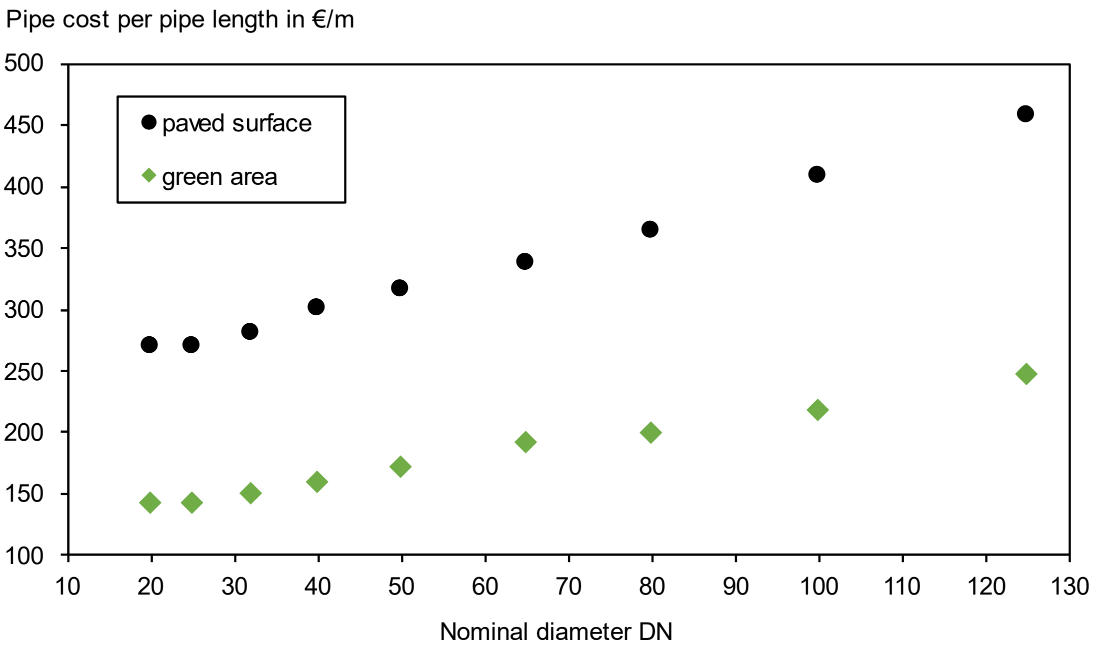


Fig. 5: Pipe costs per meter trench depending on nominal diameter and ground condition including construction costs and pipe material costs (Manderfeld et al., 2008).

Table 1: Parameters of the economic analysis

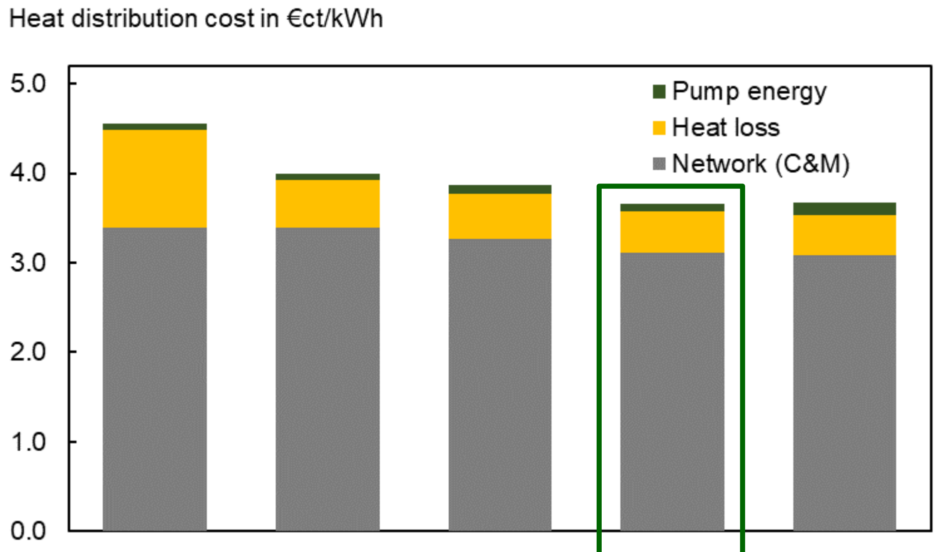
Parameter	**Value**	**Taken from**
Cost per substation	3,600 €	Stuible et al., 2016
Interest rate	2 %	DHN operator
Service life pipes	30 a	Große et al., 2017
Service life substations & pump	20 a	Große et al., 2017
Planning costs	14 % of CAPEX	HOAI (Bundesministerium für Wirtschaft und Energie (BMWi), 2013)
Operation & maintenance network	1 % of CAPEX p.a.	Große et al., 2017
Operation & maintenance substations	3 % of CAPEX p.a.	VDI 2067 (VDI-Gesellschaft Bauen und Gebäudetechnik (GBG), 2012)
Price for heat supply	45 €/MWh	DHN operator
Price for pump electricity	170 €/MWh	DHN operator

4. Results

All results are given in table 2 and the specific heat distribution costs of the different design variants of the DHN are presented in figure 6. Variant 1 uses twin pipes instead of single pipes. In addition, variant 2 is designed with a maximum specific pressure drop of 250 Pa/m instead of 120 Pa/m. As a next step, a return temperature of 45 °C instead of 60 °C is assumed for variant 3. This may require larger heat exchangers and an improved control in the substations and additional improvements of the secondary installations such as hydraulic balancing and an efficient domestic hot water preparation. These potential additional costs for these measures are not included in the economic analysis. Finally, simultaneity factors are included in the design process of the pipe segments in variant 4.

Table 2: Results of the design process and economic analysis for the DHN

Parameter	Unit	Reference	V1	V2	V3	V4
Design criteria						
Piping type	-	single	**twin**	**twin**	**twin**	**twin**
Δp_{max}	Pa/m	120	120	**250**	**250**	**250**
T_{flow} / T_{return}	°C	80 / 60	80 / 60	80 / 60	80 / **45**	80 / **45**
Simultaneity	-	none	none	none	none	**included**
Selected parameters						
Network volume	m^3	140	138	103	65	53
Pressure rating	-	PN6	PN6	PN10	PN10	PN16
Heat losses	% *)	19.5	10.7	10.1	9.3	9.1
Pump energy	% *)	0.30	0.32	0.49	0.42	0.79
				*) in relation to the annual heat input into the DHN		
Heat distribution costs						
Network costs	€ct/kWh	3.40	3.39	3.27	3.12	3.08
Heat loss costs	€ct/kWh	1.09	0.54	0.51	0.46	0.45
Pumping costs	€ct/kWh	0.06	0.06	0.09	0.08	0.15



Parameter	Reference	V1	V2	V3	V4
Piping type	single	**twin**	**twin**	**twin**	**twin**
Δp_{max} **in Pa/m**	120	120	**250**	**250**	**250**
T_{flow} / T_{return} **in °C**	80 / 60	80 / 60	80 / 60	80 / **45**	80 / **45**
Simultaneity	none	none	none	none	**included**

Fig. 6: Specific heat distribution costs of the design variants, separated into cost for the network (construction and maintenance of all components, including substations and pumps), for heat losses, and for the pump energy.

The results show that the costs for the network infrastructure (construction and maintenance) dominate for all design variants. The costs for heat losses are substantially lower while costs for pumping energy form the smallest portion.

The reference variant has high heat losses of 19.5 % of the heat input into the DHN. Its specific heat distribution costs are 4.55 €ct/kWh (in relation to the delivered heat). By using twin pipes in variant 1, the heat losses are reduced to 10.7 %. The heat distribution costs decrease by 0.56 €ct/kWh, which is almost exclusively an effect of the reduced heat losses.

Variant 2 has smaller pipe diameters (the network volume is reduced by about 25 %) due to the higher specific pressure drop that is used in the design process. In consequence, the heat distribution costs are reduced by another 0.12 €ct/kWh, which is mainly due to reduced investments for the pipe construction, while a minor increase of pump energy costs is compensated by an equal reduction of heat loss costs. This variant entails higher pressures in the network, so that a pressure rating of PN10 instead of PN6 is required for the components.

As a next step, a reduced return temperature of 45 °C instead of 60 °C is assumed for variant 3. This leads to reduced volume flow rates in the network allowing for thinner pipes, which in total leads to a reduction of the network volume by another 25 %. The total heat distribution costs show a further decrease by 0.19 €ct/kWh, which is mainly attributed to reduced costs for the network itself, while heat loss and pump energy costs decrease as well. It should be noted that this result is based on the assumption, that the reduced return temperatures can be reached during the whole year, which limits the comparability of the variants 3 and 4 with the previous design variants. However, the result shows, that when designing DHNs, the lowest possible return temperature should be aimed for and implemented, as this is favorable for all three cost components.

Including simultaneity factors in the design process of variant 4 leads to a substantial rise in pump energy costs, that are not fully compensated by reduced network and heat loss costs. This variant requires a pressure rating of PN16 for all network components.

Overall, variant 3 with twin pipes, a pipe dimensioning at 250 Pa/m and network temperatures of 80 °C supply and 45 °C return temperature is the most cost-effective solution. Compared to the reference variant, the heat distribution costs are reduced by 20 %.

5. Discussion

5.1. Additional efforts for the design variants

The design variants 1 to 4 entail individual extra efforts, that cannot be clearly quantified and that highly depend on the respective local conditions. This paragraph discusses these extra efforts in detail.

Twin pipes, as used for variants 1 to 4 may under certain circumstances lead to increased complexity of the installation, because it is more difficult to circumvent unexpected underground obstacles with this pipe system. Thus, additional bends and additional labour and expenses may be needed. The risk of this factor mainly depends on how many other underground installations will be found along the network route – and how much is known about them in advance. In very unfavourable cases, the additional effort may even lead to a situation, where for distinct areas of the DHN single pipes should be preferred to twin pipes.

The design with higher specific pressure drops entails an equivalent increase in network pressures. While the reference variant and variant 1 may be built with a pressure rating of PN6, variant 2 and 3 require PN10 and variant 4 even needs PN16. Typically, pipes and substations have at least a PN10 pressure rating (compare Koidl, 2016 and YADOS GmbH, 2016). However, components with PN16 pressure rating may entail additional costs, that could not be quantified in this work due to a lack of adequate information in the literature. In general, it is recommendable not to exceed pressure ratings by a little and rather stay within PN10 for small DHNs.

Assuming reduced return temperatures of 45 °C in the design process (variants 3 and 4) requires improvements of the secondary installations of the customers. In particular, hydraulic balancing of the heating system has to be undertaken and outdated components for domestic hot water preparation should be replaced by efficient technologies. The costs for these measures are not included in this work, as they strongly depend on the individual situation of the customer installations and cannot be reliably quantified. Furthermore, these measures lead to other positive effects: For example, hydraulic balancing substantially improves the comfort in the building (no over- and underheating), which may already justify the costs.

5.2. Transferability of the methods and results

The methods to optimally design rural DHNs described in this work can be transferred to other case studies, provided that the required data is available. The results of the case study may be transferred to other cases, if the essential parameters of the DHN (e.g. linear heat density, size of the network) and of the economic analysis (especially interest rate, heat and electricity prices) roughly coincide.

In particular, the result that twin pipes yield a substantial cost reduction due to reduced heat losses is robust and can be transferred to other small rural DHNs. Furthermore, it is generally recommendable to design small rural DHNs with a rather high specific pressure drop of about 250 Pa/m, even if the exact optimal value is subject to the costs for heat, electricity, and network construction of the individual case. In addition, striving for low return temperatures in the design phase of the network certainly leads to a cost reduction for the DHN, because all cost components decrease with decreasing return temperatures. The exact value that can be reached in the respective case however depends on the effort, that the customers must undertake to maintain this temperature in operation.

In this case study, considering simultaneity factors in the design process has not proven favorable. This result cannot be transferred to small rural DHNs in general, it rather is a consequence of the special network structure of the case study with very long transport pipes. Considering simultaneity factors leads to a change of pipe diameters by one step along the whole length of the transport pipe which entails a doubling of pressure losses in the thermo-hydraulic simulations. In contrast, for DHNs with a heat supply unit within the area of heat demand, considering simultaneity factors in the design process may be favorable. Therefore, the design method using simultaneity factors has been described in detail, so that it can be used and evaluated in other cases.

6. Summary

This contribution describes the design process of a small rural DHN and compares five design variants by a dynamic economic analysis based on results from thermo-hydraulic simulations.

Overall, a network design using twin pipes, a pipe dimensioning at 250 Pa/m and network temperatures of 80 °C flow and 45 °C return temperature is the most cost-effective solution, with heat distribution costs of 3.7 €ct/kWh. Compared to the reference variant with single pipes, pipe dimensioning at 120 Pa/m and network temperatures of 80 °C / 60 °C (flow / return), the heat distribution costs are reduced by 20 %.

In general, the common pipe dimensioning with a maximum specific pressure drop of about 100 Pa/m is not cost-optimal for small DHN. Instead, higher for the maximum specific pressure drop should be used. Furthermore, the results show that rural DHN should be designed with twin pipes and lowest-possible return temperatures to reach optimal heat distribution costs.

7. Acknowledgments

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